Primordial Circumstellar Disks in Binary Systems: Evidence for Reduced Lifetimes

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ABSTRACT

We combine the results from several multiplicity surveys of pre-main-sequence stars located in four nearby star-forming regions with *Spitzer* data from three different Legacy Projects. This allows us to construct a sample of 349 targets, including 125 binaries, which we use to to investigate the effect of companions on the evolution of circumstellar disks. We find that the distribution of projected separations of systems with *Spitzer* excesses is significantly different (P $\sim$ 2.4e-5, according to the KS test for binaries with separations < 400 AU) from that of systems lacking evidence for a disk. As expected, systems with projected separations < 40 AU are half as likely to retain at least one disk than are systems with projected separations in the 40-400 AU range. These results represent the first statistically significant evidence for a correlation between binary separation and the presence of an inner disk (r $\sim$ 1 AU). Several factors (e.g., the incompleteness of the census of close binaries, the use of unresolved disk indicators, and projection effects) have previously masked this correlation in smaller samples. We discuss the implications of our findings for circumstellar disk lifetimes and the formation of planets in multiple systems.

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1. Introduction

Early multiplicity surveys of pre-main-sequence (PMS) stars in nearby star-forming regions have established that most low-mass stars in the solar neighborhood form in multiple systems (e.g., Leinert et al. 1993; Simon et al. 1995). Understanding the effect of multiplicity on the evolution of primordial circumstellar disks, the birthplace of planets, is therefore crucial to understand the potential for planet formation in most of the stars in the Galaxy. Recent models suggest that, starting from a disk of planetary embryos and planetesimals, planets can form and survive around individual members of binary systems with separations as small as 5 AU (Quintana et al. 2007) as well as in orbits around both members of very close (r < 0.3 AU) binary systems (Quintana & Lissauer 2006). However, it is still unclear how the presence of a close companion affects the evolution of the accretion disk, and whether or not the early disruption of the primordial disk is the limiting factor for the formation of planets in multiple systems.

Recent *Spitzer* studies (Padgett et al. 2006, Cieza et al. 2007) find that up to 50% of the youngest weak-line T Tauri stars (age ∼1 Myr) show photospheric emission in the mid-IR, which implies that their planet-forming regions are extremely depleted of dust at this early age. One possible explanation for a very early disk dissipation is the efficient formation of planets in a <1 Myr timescale (e.g., Boss 2000). Another possibility is the disruption of the disk due to the presence of close companions. The outer disks around the individual stars in a binary system are expected to be tidally truncated at a fraction (∼0.3-0.5) of the binary separation (Papaloizou & Pringle 1977) and it has been suggested that the truncation of the disk limits the amount of material that can be accreted and effectively shortens the accretion timescale in close binaries (Ghez et al. 1993).

Observational studies searching for a connection between close binaries and accelerated disk dissipation have so far yielded mixed and inconclusive results. Ghez et al. (1993) performed a speckle imaging survey of 69 stars in Taurus and Ophiuchus and concluded that the incidence of close binaries (r < 50 AU) in non-accreting PMS stars (i.e., weak-line T Tauri stars, WTTSs) is enhanced with respect to that of accreting objets (i.e., classical T Tauri stars, CTTSs). However, subsequent studies have failed to confirm this conclusion. Leinert et al. (1993) and Kohler & Leinert (1998) performed larger speckle surveys in Taurus and concluded that both the total binary fraction and the distribution of projected binary separations of CTTSs and WTTSs are indistinguishable from each other. More

recently, Ratzka et al. (2005) performed a speckle multiplicity survey of 158 PMS stars in Ophiuchus, the largest to date, and found a trend in the sense that objects with Spectral Energy Distributions (SEDs) suggesting the presence of a disk have *fewer* companions but at *smaller* projected separations than that of objects with SEDs consistent with bare stellar photospheres.

Even though the truncation of disks in binary systems has very solid theoretical grounds, it has been repeatedly argued that, as long as disks in multiple systems can be replenished by an external reservoir (e.g., a circumbinary disk and/or an envelope), binaries will constrain the sizes of disks, but not necessarily reduce accretion disk lifetimes (Bouvier et al. 1997; Prato & Simon, 1997; White & Ghez 1997, Mathieu et al. 1999). As a result, the lack of a statistically significant difference in the multiplicity and/or the binary separation of stars with and without disk indicators have lead many authors to conclude that multiplicity does not affect the lifetimes of circumstellar disks and/or planet formation (e.g., Simon & Prato 1995; Armitage et al. 2003; Monin et al. 2007; Pascucci et al. 2008). Here we study a sample of 349 PMS stars, including 125 binaries with *Spitzer* data, and show that companions, at the peak of their separation distribution ($\sim$30 AU), do in fact shorten the lifetimes of circumstellar disks.

2. The Sample

We collected projected binary separations from near-IR multiplicity surveys of PMS stars located in the following nearby (d < 160 pc) star-forming regions: Ophiuchus (Simon et al., 1995; Prato 2007; Ratzka et al. 2005), Taurus (Leinert et al. 1993; Simon et al. 1995; Kohler & Leinert1998), Chameleon I (Lafreniere et al. 2008), and Corona Australis (Kohler et al. 2008).

Most of the surveys were performed using speckle imaging (Leinert et al. 1993; Kohler & Leinert 1998; Ratzka et al. 2005; Kohler et al. 2008), but we also include results from lunar occultation (Simon et al. 1995), radial velocity (Prato 2007), and adaptive optics (Lafreniere et al. 2008) surveys. The speckle and adaptive optics surveys are sensitive to binaries down to projected separations similar to the K-band diffraction limits of the 3.5-8.2 m telescope used ($\sim$0.06-0.13"), while the lunar occultation observations can detect binaries with separations as small as 0.005". The radial velocity surveys are of course sensitive to binaries at arbitrarily small separations, but are much less sensitive to wider binaries. As a result, our sample is highly heterogeneous in terms of completeness. However, as it will discussed in Section 4., the detection biases of the different surveys included in our study are unlikely to affect our conclusions.

Using their 2MASS coordinates and a $2''$ matching radius, we searched for the *Spitzer* fluxes of all the targets from the surveys discussed above in the catalogs produced by the *Cores to Disks* (Evans et al. 2003), *Taurus* (Padget et al. 2006), and *Gould Belt* (Allen et al. 2007) Legacy Projects. We focus on the IRAC 3.6 and 8.0 μm fluxes because (1) these *Spitzer* Legacy surveys are sensitive enough to reach the stellar photospheres of virtually all of the mutiplicity targets in all IRAC bands, but not so at the MIPS wavelengths, and (2) the [3.6]-[8.0] color is the best disk indicator of all IRAC colors. We found 3.6 and 8.0 μm fluxes with S/N > 5 for 349 of the mutiplicity targets, including 125 binaries. Their coordinates, projected separations (in the case of binaries), and *Spitzer* fluxes are listed in Table 1.

3. Results

3.1. Disk Identification

In order to investigate the effect of binaries in the lifetime of circumstellar disks, we first need to establish the presence or absence of a circumstellar disk in each one of the systems in our sample. We do so by using the *Spitzer* colors as a disk indicator, as shown in Fig. 1. There is a clear break in the color distribution of the sample around [3.6]-[8.0] = 0.8. Thus, we consider systems with [3.6]-[8.0] < 0.8 to be disk-less and systems with [3.6]-[8.0] > 0.8 to harbor *at least one* circumstellar disk.

Given the distances involved (125-160 pc) and *Spitzer*'s limited resolutions (2.0" FWHM at 8.0 μm), the vast majority of the multiple systems remain unresolved. As a result, except for very wide separation systems, *Spitzer* provides no information on whether the IR excess originates from one or both of the components in a binary system. The dotted vertical line in Fig. 1 corresponds to $2.4''$, the size of 2 IRAC pixels, which is the radius of the photometry apertures for the the *Taurus* Legacy Project data we use. The lower S/N components of multiple objects detected within 2 pixels of each other have been dropped from their catalogs. The *Cores to Disks* and *Gould Belt* teams performed PSF fitting photometry, but objects less than 2 pixels apart are still unlikely to be resolved.

From Fig. 1, we find that 186 of the 349 objects listed in Table 1 have an IR-excess indicating the presence of a disk, of which 72 are known to be binaries and 114 are apparently single stars. Combining the multiplicity and disk identification information, we find that the disk fraction of multiple stars is marginally *larger* than that of stars that appear to be single (57.6±4% vs 50.9 ±3%). Taken at face value, this result seems to imply that multiplicity has no effect on the evolution of circumstellar disks. However, as it will be shown in the

following sections, this initial result can easily be understood in terms of the incompleteness and biases of the multiplicity surveys and the limitations of the disk identification method.

3.2. The separation Distributions of Stars with and without a Disk

The theoretical expectation of the effect of multiplicity on circumstellar disks is that, by tidally truncating each others outer disks, close companions limit the amount of circumstellar material that can be accreted and hence reduce the lifetimes of their disks (Papaloizou & Pringle 1977). Since the dispersal timescale of a truncated disk is given by the viscous timescale at the truncation radius, one expects the lifetimes of disks in binary systems to be a strong function of the binary physical separation. This prediction can be tested by investigating the disk fraction as a function of binary projected separation, or conversely, the distributions of binary separation of systems with and without a disk. Such distributions are shown in Fig. 2, where the measured separations have been converted into projected physical separations (in AU) using the following distances: 125 for Ophichus (Loinard et al. 2008), 130 pc for Corona Australis (Casey et al. 1998), 140 pc for Taurus (Torres et al. 2007), and 160 pc for Chameleon I (Whittet et al. 1997).

Fig. 2 clearly shows that targets without an excess tend to have companions at smaller separations than targets with an excess indicating the presence of a disk. The disk fraction of the systems with separations less than 40 AU is 38.2%±6%, while the disk fraction of systems with separations in the 40-400 AU range is 77.8±7%. This difference in the disk fractions is 4.3-σ. This is a robust result as a two-sided Kolmogorov–Smirnov (KS) test shows that there is only a 2.4e-5 probability that the distributions of binary separations of targets with and without a disks have been drawn from the same parent population. Targets with projected separations > 400 AU have been excluded from these calculations because they are likely to be resolved by *Spitzer* and therefore require a different statistical analysis than the rest of the sample.

For binary systems with separations smaller than the *Spitzer* beam, the disk fractions estimated above are not an accurate representation of the true disk fractions of the individual components of the systems. Assuming that each component of a binary system has the same individual probability, DF_{ind}, of retaining a disk, the resulting fraction of systems with an IR excess, DF_{sys}, is given by the following equation: $DF_{sys}=1-(1-DF_{ind})^2$. Based on this formula, the disk fraction of the individual components of binaries systems with projected separations < 40 AU is 21.4±5%, while that of systems with separations in the 40-400 AU range is 52.9±7%, a disk fraction that is undistinguishable from that of apparently single stars, 50.9±3%. In reality, DF_{ind} is unlikely to be exactly the same for both components of

a binary system, especially if their mass ratio is high, but the above calculation illustrates well the limitations of the disk fractions derived from unresolved disk indicators.

4. Discussion and Conclusions

Although we interpret the strong correlation between disk fraction and binary separation as an evidence for reduced disk lifetimes in close binary systems, the census of binaries in our sample is incomplete, especially at small separations (see Fig. 2). Therefore, such a correlation could also arise if the older star-forming regions in our sample were observed with the techniques most sensitive to tight companions. In that case, the close binaries in our sample would be systematically older than the wide binaries and thus would have lower disk fractions. We investigate this possibility by examining the relative ages of the stars in the four different regions included in our study. Instead of adopting ages from the literature, which are known to be model dependent, we derive their relative ages from their disk fractions. Table 2 shows that the targets from Cham I and Ophiuchus have very similar disk fractions, but that the disk fraction of Taurus objects is clearly larger than that of CrA targets. Table 2 also shows that 1) virtually all the lunar occultation and radial velocity data, which are the most sensitive to close companions, come from the two youngest regions, and 2) the disk fraction of the lunar occultation plus radial velocity samples (LO+RV) are almost identical to that of the speckle plus adaptive optics samples (SP+AO). These two facts strongly suggest that our results are not affected by the incompleteness and detection biases of our heterogeneous sample. We therefore conclude that the correlation between disk fraction and binary separation is due to the effect close binaries have on primordial disk lifetimes.

4.1. Implications for Disk Lifetimes

It has already been shown that $\lesssim$ 50-100 AU separation binaries tend to have less (sub)millimeter emission than single stars or wider binaries (Osterloh & Beckwith 1995; Jensen et al. 1996; Andrews & Williams, 2005). This implies lower disk masses for close binaries, but does not rule out the existence of small (r < 30 AU) disks with surface densities large enough to allow the formation of planets (Mathieu et al. 2000). Since *Spitzer* IRAC data probe circumstellar distances of the order of 1 AU, our results show that close binaries not only reduce the sizes of disks, but also their lifetimes.

The fraction of stars with disks as a function of age observed in nearby star-forming

regions shows that there is a very wide range of primordial disk lifetimes. Some stars lose their disks well within the first Myr, while others retain their primordial disks for up to 10 Mys (Haisch et al. 2001; Cieza et al. 2007). The results from the previous section strongly suggest that reduced disk lifetimes in binary systems can account for a significant part of the observed overall dispersion in disk lifetimes.

The distribution of physical separations, a, in solar-type PMS binaries is expected to peak around 30 AU (Duquennoy & Mayor, 1991). However, the disks around most binary systems will have a truncation radius, R_T given by $R_T = 0.3\text{-}0.5 \times a \sim 10\text{-}15$ AU (Papaloizou & Pringle, 1977). These truncation radii are ~ 10 times smaller than the typical radii of disks around single stars (Andrews & Williams, 2007). The viscous timescales for a disk with a power-law surface density profile of index p, is given by $t(r) \propto r^{2-p}$. Adopting p = 1, which is consistent with both an steady state accretion disk and current observational constraints (Andrews & Williams, 2007) leads to $t(r) \propto r$. This implies that the lifetimes of disks around the individual components of most binary systems should be $\sim 10\%$ of those of single stars. Assuming disk lifetimes of 3-5 Myr for single stars, this corresponds to disk lifetimes of 0.3-0.5 Myr for binaries systems at the peak of their separation distribution. These short disk lifetimes are broadly consistent with the disk fraction of $\sim 20\%$ that we estimate for the individual components of binaries systems with projected separations < 40 AU (see Sec 3.2)

The rotation period distributions of PMS stars provide additional evidence for very early disk dissipation in a significant fraction of them. Rebull et al. (2004) and Cieza & Baliber (2007) both find that the bimodal period distribution of the Orion Nebula Cluster can only be reproduced, in the context of the disk regulation of angular momentum paradigm, if disk lifetimes are themselves bimodal, with 30-40% of the stars losing their regulating disks within <1 Myr of their formation. Such bimodal distribution is in fact expected from a population combining single and binary stars.

4.2. Implications for Planet Formation in Multiple Systems

Since most stars in the Galaxy are likely to form in multiple systems, our results on the effect of multiplicity on circumstellar disk lifetimes have direct implications for planet formation. It is now almost universally accepted that terrestrial planets form through the continuous growth of solid particles. However, there is much less of a consensus on the formation mechanism of giant planets, with core accretion (Pollack et al. 1996) and gravitation instability (Boss 2000) being the two competing leading theories.

Even though recent core accretion models (e.g., Alibert et al. 2004) can reproduce the formation of a solid core massive enough ($\sim$10 $M_\oplus$) to start accreting a gaseous envelope within a few Myrs, disk lifetimes of 0.3-0.5 Myrs are most likely to represent a significant challenge to giant planet formation through core accretion in binary systems. Reduced accretion lifetimes impose a weaker but still significant obstacle to terrestrial planet formation. Gas drag is crucial for the growth of planetesimal into planetary embryos as it reduces the relative velocity of planetesimals to a regime in which accretion can take place (Xie & Zhou, 2008). In the absence of gas, planetesimals subjected to the gravitational perturbations of a binary system are expected to sustain relative velocities well in excess of the threshold at which erosion dominates over accretion (Marzari & Scholl, 2000). Thus, in order for terrestrial planets to efficiently form in binary systems, planetary embryos should be formed before the gas dissipates.

While it seems very likely that multiplicity disfavors terrestrial planet formation in general and giant planet formation through core accretion, its effect on giant planet formation through gravitational instability remains unclear. Depending on the details of the models, it has been argued both that multiplicity inhibits (e.g., Mayer et al. 2005) and enhances (e.g., Boss 2006) planet formation through gravitational instability.

Given the limited number of currently known exoplanets in binary systems, it is not yet possible to draw statistically significant results on the incidence of planets as a function of binary separation. However, there are already some indications that giant planets are in fact underrepresented in binary systems with separations $\lesssim$50-100 AU (Eggenberg et al. 2007; Bonavita & Desidera 2007). If most giant planets form through core accretion, the findings presented herein would provide a natural explanation for such a result.

Even though many previous studies of smaller samples have searched for a connection between multiplicity and an accelerated disk dissipation (e.g., Leinert et al. 1993, Ghez et al. 1993; Simon & Prato 1995; Ratzka et al. 2005; Bouwman et al. 2006; Monin et al. 2007), the results from this Letter represent the first statistically significant (i.e., over 3-σ) evidence that binaries reduce the lifetimes of circumstellar disks. This is not too surprising considering that: (1) unresolved disk indicators only provide information on whether at least one of the components in a binary system has a disk, (2) the observed projected separations represent the *minimum* possible value of the true physical separations; thus many of the systems only appear to be tight binaries due to projection effects, and (3) the multiplicity surveys are highly incomplete for tight systems, where the effect on disk lifetimes is expected to be most severe. The combination of these three factors explains why a very large sample is necessary to reveal the effect of multiplicity on disk lifetimes.

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Table 1. Multiplicity and *Spitzer* data

Name	Ra (J2000)	Dec (J2000)	Reg	Sep (″)	*Ref*[a]	$F_{3.6}$ (mJy)	$Error_{3.6}$ (mJy)	$F_{4.5}$ (mJy)	$Error_{4.5}$ (mJy)	$F_{5.8}$ (mJy)	$Error_{5.8}$ (mJy)	$F_{8.0}$ (mJy)	$Error_{8.0}$ (mJy)
V1095 Tau	63.3090	28.3196	Tau	——	1	1.08e+02	3.95e-01	7.17e+01	2.36e-01	4.96e+01	1.98e-01	2.73e+01	9.75e-02
V1096 Tau	63.3635	28.2736	Tau	——	1	3.59e+02	6.58e-01	2.28e+02	5.54e-01	1.56e+02	5.87e-01	9.44e+01	1.82e-01
V773 Tau	63.5538	28.2034	Tau	0.170	1	1.10e+03	1.75e+00	1.03e+03	2.02e+00	1.02e+03	1.42e+00	1.13e+03	1.35e+00
FM Tau	63.5566	28.2137	Tau	——	1	1.63e+02	3.71e-01	1.53e+02	3.74e-01	1.31e+02	6.16e-01	1.73e+02	4.10e-01
FN Tau	63.5608	28.4661	Tau	——	1	2.59e+02	5.01e-01	2.43e+02	5.47e-01	2.37e+02	8.31e-01	3.22e+02	6.67e-01
CW Tau	63.5708	28.1827	Tau	——	1	1.23e+03	1.86e+00	1.22e+03	2.55e+00	1.07e+03	1.60e+00	1.01e+03	1.15e+00
CX Tau	63.6994	26.8031	Tau	——	1	1.14e+02	3.06e-01	1.01e+02	2.09e-01	9.76e+01	5.97e-01	1.42e+02	3.63e-01
V1098 Tau	63.6999	27.8763	Tau	0.470	1	3.43e+02	5.61e-01	2.09e+02	4.42e-01	1.42e+02	6.05e-01	8.21e+01	1.70e-01
FO Tau	63.7053	28.2085	Tau	0.165	1	2.73e+02	6.14e-01	2.44e+02	6.31e-01	2.35e+02	7.49e-01	2.74e+02	6.70e-01
V1068 Tau	64.1171	28.1266	Tau	——	1	1.50e+02	3.95e-01	9.66e+01	2.20e-01	6.99e+01	2.40e-01	3.86e+01	1.21e-01

Note. — The complete version of this table is in the electronic edition of the Journal.

[a]References: (1) Leinert et al. 1993; (2) Simon et al. 1995; (3) Lafreniere et al. 2008; (4) Prato et al. 2007; (5) Ratzka et al. 2005; (6) Kohler et al. 2008.

Table 2.   Properties of the Sample

Sample	# of Targets by Technique				Targets (total #)	Sin (#)	Bin (#)	Disk (#)	Diskless (#)	DF (%)	Relative Age
	SP	AO	LO	RV							
Tau Region	65	0	46	0	84	43	41	54	30	64.3±5	youngest
Oph Region	141	0	33	19	158	108	50	83	75	52.5±4	young
Cham I Region	0	91	0	0	91	65	26	45	46	49.5±5	old
CrA Region	16	0	0	1	16	8	8	4	12	25.0±11	oldest
LO+RV sample	0	0	79	20	98	50	48	57	41	58.2±5	
SP+AO sample	222	91	0	0	313	202	111	172	141	55.0±3	

Note. — SP+AO+LO+RV is sometimes greater than the total number of targets because some overlap exists among some of the sub-samples.
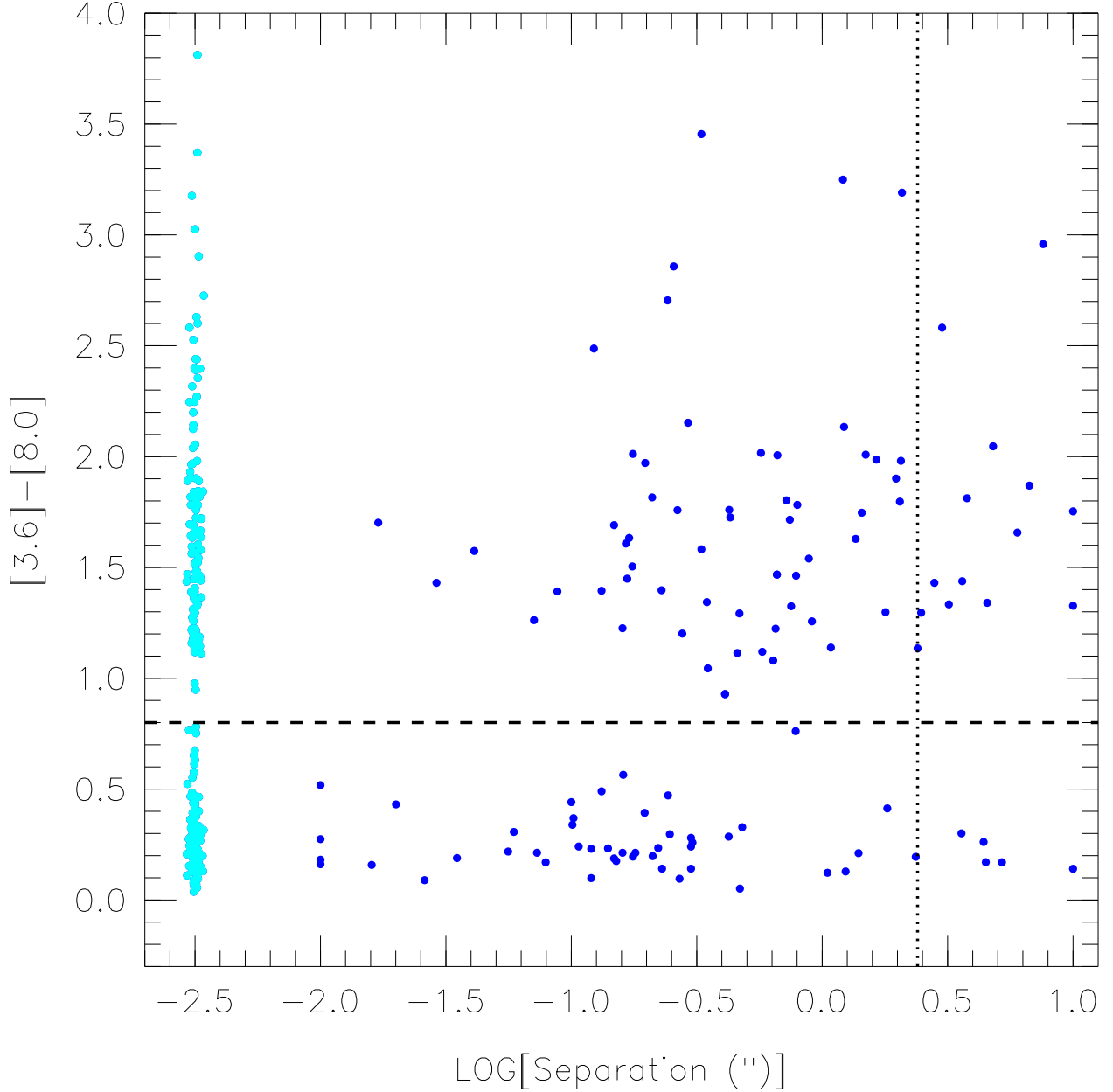
Fig. 1.— [3.6]-[8.0] vs projected separation for our entire sample to illustrate our disk identification criterion. Systems with [3.6]-[8.0] < 0.8 are considered to be disk-less, while systems with [3.6]-[8.0] > 0.8 are considered to harbor *at least* one disk. The dotted vertical line corresponds to 2.4", the angle sustained by 2 IRAC pixels. Only the few objects to the *right* of this line are likely to be resolved by *Spitzer*. Spectroscopic binaries have been assigned a separation of 0.01". Single stars, shown in light blue, have been assigned a logarithmic separation of -2.5 plus very small random offsets to better show the density of objects at a given color.
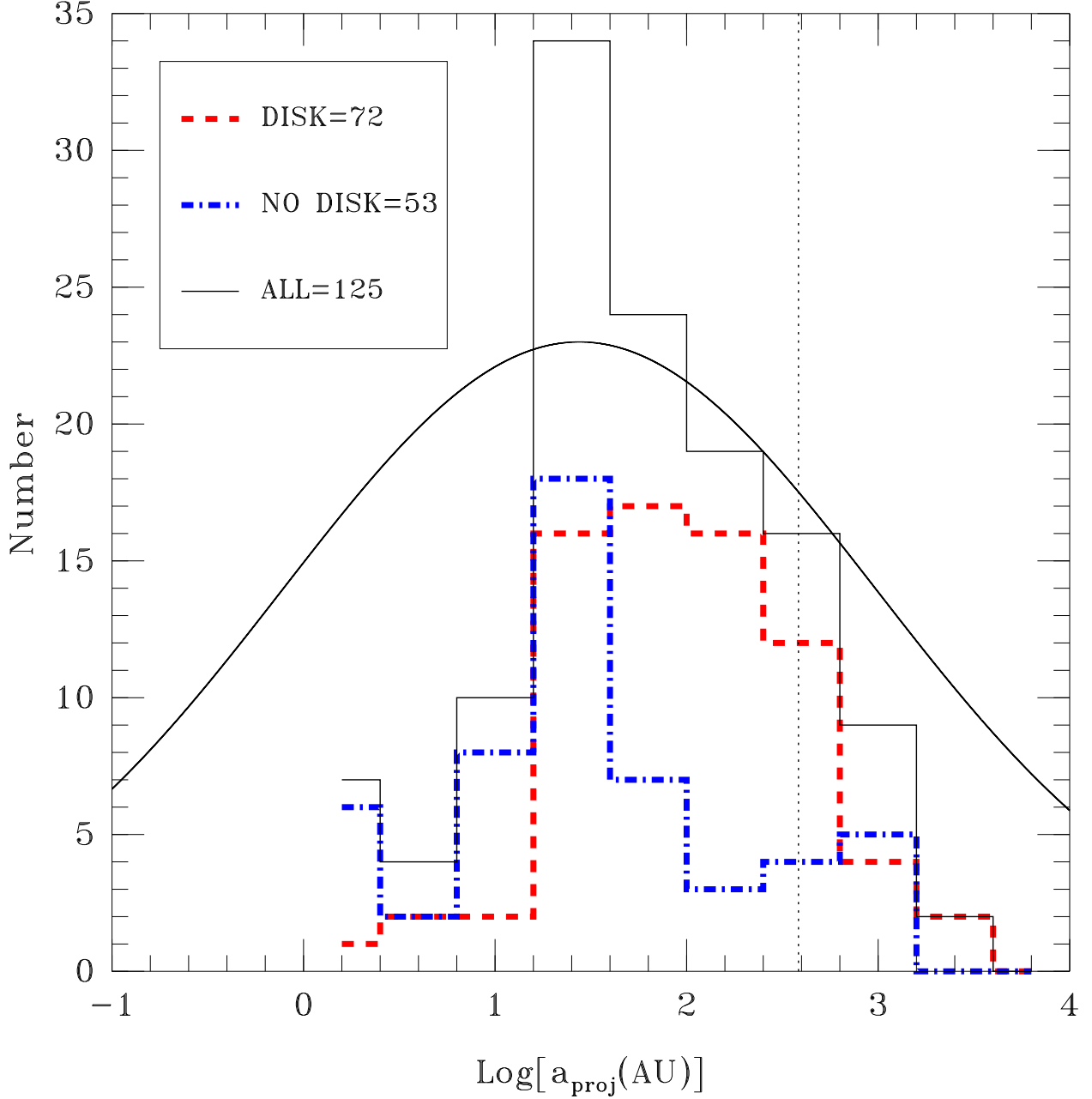
Fig. 2.— The histogram of projected separations for targets with and without *Spitzer* excesses indicating the presence of a disk. Systems without an excess clearly tend to have smaller separations. The solid curve represents the distribution of binaries in solar-type stars (Duquennoy & Mayor, 1991). The census of companions is still highly incomplete for separations $\lesssim 20$ AU. The vertical dotted line at X= 2.58 = LOG(384 AU) corresponds to the resolution of 2 IRAC pixels (2.4") at 160 pc, the distance of the farthest regions in our sample. Systems to the *right* of this line are likely to be resolved by *Spizter*. This explains their lower disk fraction, as we are measuring their DF_{ind} instead of DF_{sys}.